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On Parameter Estimation of Space Manipulator Systems with Flexible Joints Using the Energy Balance*

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Abstract. The parameter estimation of space manipulator systems on orbit is studied, whose manipulators are subject to joint flexibilities. To improve path planning and tracking capabilities, advanced control strategies that benefit from the knowledge of system parameters are required. These parameters include the system inertial parameters as well as the stiffness and damping parameters, which describe joint flexibilities. During operation some of these parameters may change or be unknown. Estimation methods based on the equations of motion are sensitive to noise, while methods based on the angular momentum conservation, while they are tolerant to noise, they cannot estimate the parameters that describe joint flexibilities. A parameter estimation method, based on the energy balance, applied during the motion of a space flexible-joint manipulator system in the free-floating mode, is developed. The method is tolerant to noise and can reconstruct the system full dynamics. It is shown that the parameters estimated by the proposed method can describe the system dynamics fully. The application of the developed method is valid for spatial systems; it is illustrated by a planar 7 degrees of freedom (DoF) example system.

I. Introduction

On-Orbit Servicing (OOS) will require lightweight and dexterous space robotics systems, carrying manipulators subject to joint flexibilities, Fig. 1. Considering flexibilities only at the joint level is reasonable for systems with short links, such as the free-floating/free-flying space manipulator systems under study, or for flown systems in past and current OOS missions. Examples of OOS missions are the Japanese ETS-VII [1] and the US Orbital Express [2], and more recently the missions DEOS [3] and e.Deorbit [4]. Such flexibilities may result in poor performance when manipulating large payloads, and in some cases even in instabilities, if neglected in the control design. Advanced control strategies will be required, which will need knowledge of system parameters.

Several studies exist for the parameter estimation of rigid-joint free-floating space manipulator systems (FFSMS) based on the equations of motion, or on the angular momentum conservation. The parameter identification of a FFSMS without flexibilities and equipped with torque sensors was studied in [5]. Exploiting the conservation of the angular momentum of a FFSMS, an estimation method was developed where the parameters to be identified were combinations of rigid spacecraft, manipulator and payload parameters; once available, they were enough to reconstruct the system full dynamics as required in model-based control laws, [6].

In [7], the effects of flexible appendages and liquid fuel sloshing on the rigid body parameter identification were addressed. To model the liquid fuel sloshing effect, a mechanical pendulum was considered. It was shown that in both cases significant influences to the identification model appear; an improvement can be achieved by appropriate optimization of the exciting trajectories. To estimate the joint flexibilities of a space manipulator, the development of a simplified coplanar model of the flexible joint was proposed [8]. The joint stiffnesses and damping were found by applying an impact force on the system and studying the resulting responses.

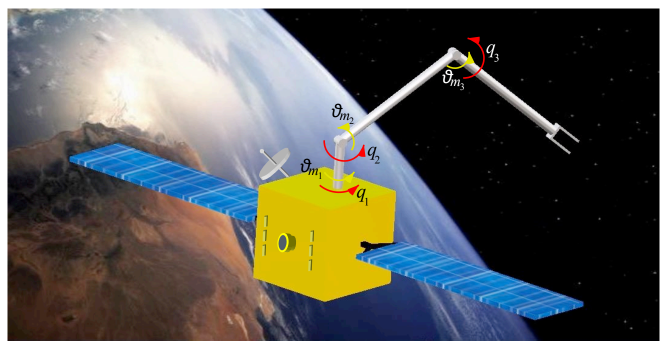

Fig. 1. A spatial FFSMS with flexible joints.

To generate exciting trajectories for the identification of the inertial parameters of a rigid joint fixed-base manipulator, the energy model was proposed, since the energy is a function of joint angles and rates, and does not require calculation or measurement of accelerations [9]. In [10], the authors propose the Power Identification Model (PIM), since derivation is much simpler than the derivation of the Inverse Dynamic Identification Model (IDIM). However, it was shown that the PIM is much more sensitive to the choice of the exciting trajectories than the IDIM. More recently, a method for estimating inertial parameters of a free-flying space manipulator after grasping an object has been proposed [11]. To optimize the exciting trajectory, an approach based on the energy balance between the actuation work and the rate of change of kinetic energy was introduced to yield the number of Fourier series harmonics used to represent the executed trajectory.

In this paper, the estimation of the full dynamics of a FFSMS with flexible joints is studied. It is shown that the methods based on the angular momentum conservation, which are tolerant to sensor noise, cannot estimate joint flex-

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ibility parameters. A new parameter estimation method, based on the energy balance during the motion of a flexible-joint FFSMS, is proposed. The method estimates all system parameters including those that describe the joint flexibilities, requiring only measurements of joint angles and rates, spacecraft attitude and angular velocity, and joint torques. In contrast to the methods based on the equations of motion, the developed method is insensitive to sensor noise, since no information about spacecraft and joint accelerations, is required. The application of the proposed method is valid for spatial systems. It is shown that the parameters estimated by the proposed method can describe the system full dynamics sufficiently**.** The method is illustrated by a planar 7 degrees of freedom (DoF) flexible-joint FFSMS.

II. DYNAMICS OF FLEXIBLE-JOINT FFSMS

Space manipulator systems consist of one or more robotic manipulators, which are mounted on a satellite base equipped with thrusters and reaction wheels. Such systems are subject to manipulator joint flexibilities. The equations of motion of a flexible-joint FFSMS with zero angular momentum have been presented analytically in [12]. In this section, we develop briefly the angular momentum conservation and the equations of motion of a flexible-joint FFSMS with non-zero angular momentum.

The DoFs of the manipulator of a flexible-joint FFSMS are twice the number of control inputs, since due to the joint flexibilities the motion of both the link and gear motor angular position q and θ_m, need to be considered, see Fig. 2.

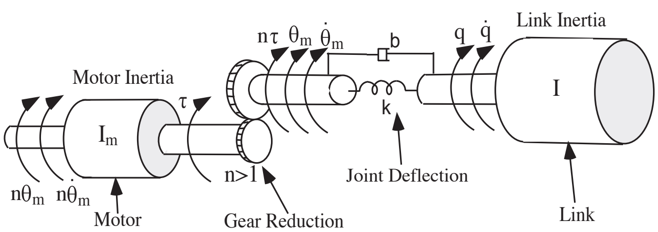

Fig. 2. The flexible joint model.

To build the model, the following assumptions are employed. First, joint deflections are considered small enough so that they can be described by a torsion spring of constant stiffness k, and a damping element of constant damping b. The joint deflections are considered to be lumped after the gearboxes, while the actuator rotors are modeled as rigid bodies, which have their Center of Mass (CoM) on the rotation axis. The motor stators are considered as mounted on manipulator links. Moreover, the motor of joint i is mounted on link i-1 and moves link i with its rotation axis aligned with the i-th joint. Finally, the stiffness of the gearbox is included in the spring/damper model and any backlash in the gears can considered negligible (e.g. using spring-loaded gears or harmonic drives). Under the above assumptions, the angular momentum conservation and the equations of motion of a flexible-joint FFSMS are derived.

A. Angular Momentum Conservation

In the free-floating mode, the CoM of a space manipulator system does not accelerate, and the system linear and angular momenta are constant. Considering zero initial linear momentum, the system CoM remains fixed in inertial space.

Then, the angular momentum of a N link flexible-joint FFSMS with respect to its CoM, $\mathbf{h_{CM}}$, expressed in the inertial frame, is given by [12]

$$\mathbf{h_{CM}}=\mathbf{R_0}(\boldsymbol{\varepsilon},n)({}^{\mathbf{0}}\mathbf{D}^{*}\,{}^{\mathbf{0}}\boldsymbol{\omega}_{\mathbf{0}}+{}^{\mathbf{0}}\mathbf{D}_{\Theta}\dot{\boldsymbol{\Theta}}) \tag{1}$$

where ${}^{\mathbf{0}}\boldsymbol{\omega}_{\mathbf{0}}$ is the spacecraft angular velocity with respect to the spacecraft 0^{th} frame, and $\mathbf{R_0}(\boldsymbol{\varepsilon},n)$ is the rotation matrix between the spacecraft and the inertial frame expressed as a function of the spacecraft Euler parameters $\boldsymbol{\varepsilon},n$. The matrices ${}^{\mathbf{0}}\mathbf{D}^{*}$ and ${}^{\mathbf{0}}\mathbf{D}_{\Theta}$ are inertia-type matrices of appropriate dimensions, given in [12], and

$$\boldsymbol{\Theta}=\begin{bmatrix}\mathbf{q}\\ \boldsymbol{\theta}_{\mathbf{m}}\end{bmatrix} \tag{2}$$

where $\mathbf{q}$ contains the manipulator joint angles

$$\mathbf{q}=\begin{bmatrix} q_1 & q_2 & \cdots & q_N\end{bmatrix}^{\mathrm{T}} \tag{3}$$

and $\boldsymbol{\theta}_{\mathbf{m}}$ is the angular position after the gearboxes

$$\boldsymbol{\theta}_{\mathbf{m}}=\begin{bmatrix} \theta_{m_1} & \theta_{m_2} & \cdots & \theta_{m_N}\end{bmatrix}^{\mathrm{T}} \tag{4}$$

B. Equations of Motion of Flexible Joint FFSMS

The equations of motion of the FFSMS are derived using the Lagrangian approach. In the case of flexible-joint FFSMS, only the potential energy due to joint flexibility is considered and given by

$$T_{flex}(\boldsymbol{\Theta})=\frac{1}{2}(\boldsymbol{\theta}_{\mathbf{m}}-\mathbf{q})^{\mathrm{T}}\mathbf{K}(\boldsymbol{\theta}_{\mathbf{m}}-\mathbf{q}) \tag{5}$$

since the potential energy due to gravity can be assumed to be zero for systems on orbit. A dissipation term is also considered and given by:

$$P_{diss}(\dot{\boldsymbol{\Theta}})=\frac{1}{2}(\dot{\boldsymbol{\theta}}_{\mathbf{m}}-\dot{\mathbf{q}})^{\mathrm{T}}\mathbf{B}(\dot{\boldsymbol{\theta}}_{\mathbf{m}}-\dot{\mathbf{q}}) \tag{6}$$

where

$$\mathbf{K}=diag(k_1,k_2,...,k_N) \tag{7}$$

$$\mathbf{B}=diag(b_1,b_2,...,b_N) \tag{8}$$

The equations of motion of flexible-joint FFSMS are [12]

$${}^{\mathbf{0}}\mathbf{D}^{*}\,{}^{\mathbf{0}}\dot{\boldsymbol{\omega}}_{\mathbf{0}}+{}^{\mathbf{0}}\mathbf{D}_{\Theta}\ddot{\boldsymbol{\Theta}}+\mathbf{C}_1^{*}=\mathbf{0} \tag{9}$$

$$\begin{aligned}&{}^{\mathbf{0}}\mathbf{D}_{\Theta}^{\mathbf{T}}\,{}^{\mathbf{0}}\dot{\boldsymbol{\omega}}_{\mathbf{0}}+{}^{\mathbf{0}}\mathbf{D}_{\Theta\Theta}\ddot{\boldsymbol{\Theta}}+\mathbf{C}_2^{*}\\ &+\begin{bmatrix}\mathbf{-K}\\ \mathbf{K}\end{bmatrix}(\boldsymbol{\theta}_{\mathbf{m}}-\mathbf{q})+\begin{bmatrix}\mathbf{-B}\\ \mathbf{B}\end{bmatrix}(\dot{\boldsymbol{\theta}}_{\mathbf{m}}-\dot{\mathbf{q}})=\mathbf{Q}\end{aligned} \tag{10}$$

where $\mathbf{C}_1^{*}$, $\mathbf{C}_2^{*}$ are column vectors containing the nonlinear terms of centrifugal and Coriolis forces and ${}^{\mathbf{0}}\mathbf{D}_{\Theta\Theta}$ is an inertia type matrix, [12].

The vector of generalized forces $\mathbf{Q}$ is

$$\mathbf{Q}=\begin{bmatrix}\mathbf{0}_{N\times 1}\\ \mathbf{n}\cdot\boldsymbol{\tau}\end{bmatrix} \tag{11}$$

where $\mathbf{n}$ is an $N\times N$ diagonal matrix of the reduction ratios

$$\mathbf{n}=diag(n_1,n_2,...,n_N) \tag{12}$$

and $\boldsymbol{\tau}$ is the column vector of the motor torques,

$$\boldsymbol{\tau}=\left[\,\tau_1\ \tau_2\ \cdots\ \tau_N\,\right]^{\mathrm{T}} \tag{13}$$

where τ_i is the torque applied on the rotor of joint i.

The above equations of motion are valid for FFSMS regardless of whether the system angular momentum is zero or not. This form of equations is suitable for system estimation, since one can exploit the property of linearity of the system model with respect to a suitable set of parameters [6].

However, when designing control systems for flexible-joint FFSMS, it is preferable to describe the system dynamics by the $2N$ reduced equations of motion. Unlike the case of equations of motion, the reduced equations of motion also require the use of the angular momentum conservation. The effect of non-zero angular momentum, for rigid-joint FFSMS, has been studied in [13]. Considering a similar procedure followed in [13], one can finally obtain the following reduced equations of motion in the presence of *nonzero* angular momentum:

$$\mathbf{H}(\boldsymbol{\Theta})\ddot{\boldsymbol{\Theta}}+\mathbf{C}^{*}(\boldsymbol{\varepsilon},n,\boldsymbol{\Theta},\dot{\boldsymbol{\Theta}},\mathbf{h}_{\mathbf{CM}})\dot{\boldsymbol{\Theta}}+\mathbf{g}_{\mathbf{h}}(\boldsymbol{\varepsilon},n,\boldsymbol{\Theta},\mathbf{h}_{\mathbf{CM}})=\mathbf{Q} \tag{14}$$

where $\mathbf{H}(\boldsymbol{\Theta})$ is an $2N\times 2N$ positive definite symmetric matrix, called the reduced system inertia matrix, equal to

$$\mathbf{H}(\boldsymbol{\Theta})={}^{\mathbf{0}}\mathbf{D}_{\boldsymbol{\Theta\Theta}}-{}^{\mathbf{0}}\mathbf{D}_{\boldsymbol{\Theta}}^{\mathrm{T}}\,{}^{\mathbf{0}}\mathbf{D}^{*-1}\,{}^{\mathbf{0}}\mathbf{D}_{\boldsymbol{\Theta}} \tag{15}$$

where the $2N\times 2N$ matrix $\mathbf{C}^{*}(\boldsymbol{\varepsilon},n,\boldsymbol{\Theta},\dot{\boldsymbol{\Theta}},\mathbf{h}_{\mathbf{CM}})$ is a function of the system angular momentum and contains the nonlinear Coriolis and centrifugal terms,

$$\mathbf{C}^{*}(\boldsymbol{\varepsilon},n,\boldsymbol{\Theta},\dot{\boldsymbol{\Theta}},\mathbf{h}_{\mathbf{CM}})=\mathbf{C}(\boldsymbol{\Theta},\dot{\boldsymbol{\Theta}})+\mathbf{C}_{\mathbf{h}}(\boldsymbol{\varepsilon},n,\boldsymbol{\Theta},\mathbf{h}_{\mathbf{CM}}) \tag{16}$$

The $2N\times 2N$ matrix $\mathbf{C}(\boldsymbol{\Theta},\dot{\boldsymbol{\Theta}})$ contains the non-linear Coriolis and centrifugal terms for a spatial FFSMS with zero angular momentum, and the $2N\times 2N$ matrix $\mathbf{C}_{\mathbf{h}}$ is an additional term caused by the presence of the system non-zero angular momentum and given by

$$\mathbf{C}_{\mathbf{h}}=\frac{\partial({}^{\mathbf{0}}\mathbf{D}_{\boldsymbol{\Theta}}^{\mathrm{T}}\,{}^{\mathbf{0}}\mathbf{D}^{*-1}\mathbf{R}_{\mathbf{0}}^{\mathrm{T}}\mathbf{h}_{\mathbf{CM}})}{\partial\boldsymbol{\Theta}}-\frac{\partial(\mathbf{h}_{\mathbf{CM}}^{\mathrm{T}}\mathbf{R}_{\mathbf{0}}\,{}^{\mathbf{0}}\mathbf{D}^{*-1}\,{}^{\mathbf{0}}\mathbf{D}_{\boldsymbol{\Theta}})}{\partial\boldsymbol{\Theta}} \tag{17}$$

The $2N\times 1$ vector $\mathbf{g}_{\mathbf{h}}$ is caused by the presence of angular momentum, too. It does not vanish for zero link and motor rates $\dot{\mathbf{q}},\dot{\boldsymbol{\theta}}_{\mathbf{m}}$ and is given by

$$\begin{aligned}\mathbf{g}_{\mathbf{h}}=&\frac{1}{2}\frac{\partial(\mathbf{h}_{\mathbf{CM}}^{\mathrm{T}}\mathbf{R}_{\mathbf{0}}\,{}^{\mathbf{0}}\mathbf{D}^{*-1}\mathbf{R}_{\mathbf{0}}^{\mathrm{T}})}{\partial\boldsymbol{\Theta}}\mathbf{h}_{\mathbf{CM}}\\&-{}^{\mathbf{0}}\mathbf{D}_{\boldsymbol{\Theta}}^{\mathrm{T}}\,{}^{\mathbf{0}}\mathbf{D}^{*-1}[{}^{\mathbf{0}}\mathbf{D}^{*-1}(\mathbf{R}_{\mathbf{0}}^{\mathrm{T}}\mathbf{h}_{\mathbf{CM}}-{}^{\mathbf{0}}\mathbf{D}_{\boldsymbol{\Theta}}\dot{\boldsymbol{\Theta}})]^{\times}\mathbf{R}_{\mathbf{0}}^{\mathrm{T}}\mathbf{h}_{\mathbf{CM}}\end{aligned} \tag{18}$$

where the symbol $(\cdot)^{\times}$, called cross-product operator, denotes the construction of a skew-symmetric matrix from the elements of the vector $(\cdot)$.

III. Parameter Estimation Using the Angular Momentum Conservation or the Eqs. of Motion

In this section, the estimation methods based on the angular momentum conservation (*AMC method*) and on the dynamic equations of motion (*DE method*) are presented briefly.

A. AMC Method

The angular momentum conservation for a flexible-joint FFSMS is given by (1). Similar to the case of rigid-joint FFSMS, this equation can be expressed linearly with respect to a vector of the parameters $\boldsymbol{\pi}_{\mathbf{h}}$ to be estimated

$$\mathbf{h}_{\mathbf{CM}}=\mathbf{Y}_{\mathbf{h}}(\dot{\mathbf{q}},\mathbf{q},\dot{\boldsymbol{\theta}}_{\mathbf{m}},{}^{\mathbf{0}}\boldsymbol{\omega}_{\mathbf{0}},\boldsymbol{\varepsilon},\eta)\boldsymbol{\pi}_{\mathbf{h}} \tag{19}$$

where the regressor matrix $\mathbf{Y}_{\mathbf{h}}$ does not require acceleration measurements.

However, although with this method the inertial parameters can be identified, the dynamics of the flexible joints described by the torsional springs and damping elements, cannot be identified. This is because, the vector of the estimated parameters $\boldsymbol{\pi}_{\mathbf{h}}$ does not contain the stiffness k_i and the damping b_i of joint i, required to describe the joint i flexibility, and therefore the method cannot estimate the full dynamics of flexible-joint FFSMS.

B. DE Method

In the case of flexible-joint FFSMS, the reduced equations of motion, (14), cannot be written in a linear form with respect to the inertial parameters. The non-linearity is caused by the presence of the term ${}^{\mathbf{0}}\mathbf{D}^{*-1}$ in $\mathbf{H}(\boldsymbol{\Theta})$, see (15). However, the equations of motion, given by Eqs. (9) - (10), can be expressed linearly with respect to the vector of the parameters $\boldsymbol{\pi}_{\boldsymbol{\tau}}$ to be estimated

$$\begin{aligned}\mathbf{0}=&{}^{\mathbf{0}}\mathbf{D}^{*}\,{}^{\mathbf{0}}\dot{\boldsymbol{\omega}}_{\mathbf{0}}+{}^{\mathbf{0}}\mathbf{D}_{\boldsymbol{\Theta}}\ddot{\boldsymbol{\Theta}}+\mathbf{C}_1^{*}\\=&\mathbf{Y}_{\mathbf{1}}(\ddot{\mathbf{q}},\dot{\mathbf{q}},\mathbf{q},\ddot{\boldsymbol{\theta}}_{\mathbf{m}},\dot{\boldsymbol{\theta}}_{\mathbf{m}},\boldsymbol{\theta}_{\mathbf{m}},{}^{\mathbf{0}}\dot{\boldsymbol{\omega}}_{\mathbf{0}},{}^{\mathbf{0}}\boldsymbol{\omega}_{\mathbf{0}})\boldsymbol{\pi}_{\boldsymbol{\tau}}\end{aligned} \tag{20}$$

$$\begin{aligned}\mathbf{Q}=&{}^{\mathbf{0}}\mathbf{D}_{\boldsymbol{\Theta}}^{\mathrm{T}}\,{}^{\mathbf{0}}\dot{\boldsymbol{\omega}}_{\mathbf{0}}+{}^{\mathbf{0}}\mathbf{D}_{\boldsymbol{\Theta\Theta}}\ddot{\boldsymbol{\Theta}}+\mathbf{C}_2^{*}+\mathbf{K}^{*}(\boldsymbol{\theta}_{\mathbf{m}}-\mathbf{q})+\mathbf{B}^{*}(\dot{\boldsymbol{\theta}}_{\mathbf{m}}-\dot{\mathbf{q}})\\=&\mathbf{Y}_{2}(\ddot{\mathbf{q}},\dot{\mathbf{q}},\mathbf{q},\ddot{\boldsymbol{\theta}}_{\mathbf{m}},\dot{\boldsymbol{\theta}}_{\mathbf{m}},\boldsymbol{\theta}_{\mathbf{m}},{}^{\mathbf{0}}\dot{\boldsymbol{\omega}}_{\mathbf{0}},{}^{\mathbf{0}}\boldsymbol{\omega}_{\mathbf{0}})\boldsymbol{\pi}_{\boldsymbol{\tau}}\end{aligned} \tag{21}$$

where

$$\mathbf{K}^{*}=\begin{bmatrix}\mathbf{-K}\\\mathbf{K}\end{bmatrix} \tag{22}$$

$$\mathbf{B}^{*}=\begin{bmatrix}\mathbf{-B}\\\mathbf{B}\end{bmatrix} \tag{23}$$

Eqs. (20) and (21) can be combined to yield

$$\mathbf{Q}^{*}=[\ \mathbf{0}^{\mathrm{T}}\ \ \mathbf{Q}^{\mathrm{T}}\ ]^{\mathrm{T}}=\mathbf{Y}_{\boldsymbol{\tau}}(\ddot{\mathbf{q}},\dot{\mathbf{q}},\mathbf{q},\ddot{\boldsymbol{\theta}}_{\mathbf{m}},\dot{\boldsymbol{\theta}}_{\mathbf{m}},\boldsymbol{\theta}_{\mathbf{m}},{}^{\mathbf{0}}\dot{\boldsymbol{\omega}}_{\mathbf{0}},{}^{\mathbf{0}}\boldsymbol{\omega}_{\mathbf{0}})\boldsymbol{\pi}_{\boldsymbol{\tau}} \tag{24}$$

where the regressor matrix is given by

$$\mathbf{Y}_{\boldsymbol{\tau}}=[\mathbf{Y}_{\mathbf{1}}^{\mathrm{T}}\ \ \mathbf{Y}_{2}^{\mathrm{T}}\ ]^{\mathrm{T}} \tag{25}$$

If N measurements of joint torques $\boldsymbol{\tau}$, link and motor positions $\mathbf{q},\boldsymbol{\theta}_{\mathbf{m}}$, link and motor velocities $\dot{\mathbf{q}},\dot{\boldsymbol{\theta}}_{\mathbf{m}}$, link and motor accelerations $\ddot{\mathbf{q}},\ddot{\boldsymbol{\theta}}_{\mathbf{m}}$ and spacecraft angular velocity ${}^{\mathbf{0}}\boldsymbol{\omega}_{\mathbf{0}}$ and acceleration ${}^{\mathbf{0}}\dot{\boldsymbol{\omega}}_{\mathbf{0}}$ can be obtained at time instants $t_1,t_2,...,t_N$ along an appropriate trajectory, one obtains the following system of equations

$$\hat{\boldsymbol{\tau}}^{*}=\begin{bmatrix}\boldsymbol{\tau}^{*}(t_1)\\\boldsymbol{\tau}^{*}(t_2)\\\vdots\\\boldsymbol{\tau}^{*}(t_N)\end{bmatrix}=\begin{bmatrix}\mathbf{Y}_{\boldsymbol{\tau}}(t_1)\\\mathbf{Y}_{\boldsymbol{\tau}}(t_2)\\\vdots\\\mathbf{Y}_{\boldsymbol{\tau}}(t_N)\end{bmatrix}\boldsymbol{\pi}_{\boldsymbol{\tau}}=\hat{\mathbf{Y}}_{\boldsymbol{\tau}}\boldsymbol{\pi}_{\boldsymbol{\tau}} \tag{26}$$

To solve (26) for $\boldsymbol{\pi}_{\boldsymbol{\tau}}$, the regressor matrix $\hat{\mathbf{Y}}_{\boldsymbol{\tau}}$ must be of full rank. To avoid ill-conditioning of matrix $\hat{\mathbf{Y}}_{\boldsymbol{\tau}}$, the number of time instants should be large enough. In this case, the system of (26) is over-determined and solving it by a least-squares technique leads to the solution in the form,

$$\boldsymbol{\pi}_{\boldsymbol{\tau}}=(\hat{\mathbf{Y}}_{\boldsymbol{\tau}}^{\mathrm{T}}\hat{\mathbf{Y}}_{\boldsymbol{\tau}})^{-1}\hat{\mathbf{Y}}_{\boldsymbol{\tau}}^{\mathrm{T}}\hat{\boldsymbol{\tau}}^{*} \tag{27}$$

where $(\hat{\mathbf{Y}}_{\boldsymbol{\tau}}^{\mathrm{T}}\hat{\mathbf{Y}}_{\boldsymbol{\tau}})^{-1}\hat{\mathbf{Y}}_{\boldsymbol{\tau}}^{\mathrm{T}}$ is the left pseudo-inverse matrix of $\hat{\mathbf{Y}}_{\boldsymbol{\tau}}$.

Note that the estimation method based on the equations of motion is sensitive to measurement noise since it requires measurements of the spacecraft angular acceleration ${}^{\mathbf{0}}\dot{\boldsymbol{\omega}}_{\mathbf{0}}$ and the link and motor accelerations $\ddot{\mathbf{q}}$ and $\ddot{\boldsymbol{\theta}}_{\mathbf{m}}$, which all contain substantial noise.

Here, it is assumed that the spacecraft angular velocity and acceleration are measured by an Inertial Measurement Unit (IMU). If ${}^{\mathbf{0}}\boldsymbol{\omega}_{\mathbf{0}}$ is the true angular velocity and ${}^{\mathbf{0}}\tilde{\boldsymbol{\omega}}_{\mathbf{0}}$ is the corresponding measurement of the angular velocity, then the measurements can be modeled by, [14]

$${}^{\mathbf{0}}\tilde{\boldsymbol{\omega}}_{\mathbf{0}}={}^{\mathbf{0}}\boldsymbol{\omega}_{\mathbf{0}}+\mathbf{b}_{\omega}+\mathbf{n}_{\omega} \tag{28}$$

$$\dot{\mathbf{b}}_{\omega}=\mathbf{n}_{\mathrm{b}\omega} \tag{29}$$

where the term $\mathbf{b}_{\omega}$ is the gyroscope bias, considered to be a "Brownian" motion process, while the terms $\mathbf{n}_{\omega}$ and $\mathbf{n}_{b\omega}$ represent white Gaussian noise with zero mean and standard deviations σ_{ω} and $\sigma_{b\omega}$, respectively.

Considering that encoders are available on the links and the brushless DC motors, the output of the encoders includes noise

$$\tilde{\mathbf{q}}=\mathbf{q}+\mathbf{n}_{\mathrm{q}} \tag{30}$$

$$\tilde{\boldsymbol{\theta}}_{\mathbf{m}}=\boldsymbol{\theta}_{\mathbf{m}}+\mathbf{n}_{\theta_{\mathrm{m}}} \tag{31}$$

where $\mathbf{q}$ and $\boldsymbol{\theta}_{\mathbf{m}}$ are the actual link and motor angles and $\tilde{\mathbf{q}}$ and $\tilde{\boldsymbol{\theta}}_{\mathbf{m}}$ the corresponding measurements; the terms $\mathbf{n}_{q}$ and $\mathbf{n}_{\theta_{\mathrm{m}}}$ represent Gaussian noise with zero mean and standard deviation σ_{pos}.

If q is the precision of encoder position and ΔT is the sample period, then the encoder noise, velocity and acceleration variances can be given by [15]

$$\begin{aligned}\sigma_{pos}^{2}&=\frac{q^{2}}{12}\\ \sigma_{vel}^{2}&=\frac{2}{\Delta T^{2}}\frac{q^{2}}{12}\\ \sigma_{accel}^{2}&=\frac{4}{\Delta T^{4}}\frac{q^{2}}{12}\end{aligned} \tag{32}$$

respectively.

IV. Parameter Estimation Using the Energy Balance

In the previous section, we concluded that both DE and AMC methods are not appropriate for estimating the parameters of flexible-joint FFSMS. The former is sensitive to noise measurements since it requires the measurements of the spacecraft angular acceleration ${}^{\mathbf{0}}\dot{\boldsymbol{\omega}}_{\mathbf{0}}$ and both the link and gear reduction angular acceleration $\ddot{\mathbf{q}}$ and $\ddot{\boldsymbol{\theta}}_{\mathbf{m}}$, respectively. The latter, although it does not require accelerations, it can estimate only the system inertial parameters but not the ones that describe the joint flexibility.

In this section, an estimation method based on the system energy balance (*EB method*) is developed. This method can be applied to the parameter estimation of flexible-joint FFSMS, since as it will be shown, it tolerates measurement noise and can estimate all parameters required for the system dynamics including those that describe the joint flexibilities.

The kinetic energy of a flexible-joint FFSMS, including motor inertial properties, is given by, [12]

$$T=\frac{1}{2}{}^{\mathbf{0}}\boldsymbol{\omega}_{\mathbf{0}}^{\mathrm{T}}\,{}^{\mathbf{0}}\mathbf{D}^{*}\,{}^{\mathbf{0}}\boldsymbol{\omega}_{\mathbf{0}}+{}^{\mathbf{0}}\boldsymbol{\omega}_{\mathbf{0}}^{\mathrm{T}}\,{}^{\mathbf{0}}\mathbf{D}_{\Theta}\dot{\boldsymbol{\Theta}}+\frac{1}{2}\dot{\boldsymbol{\Theta}}^{\mathrm{T}}\mathbf{D}_{\Theta\Theta}\dot{\boldsymbol{\Theta}} \tag{33}$$

Since the flexibility of the joint i is modeled using an elastic torsion spring of constant stiffness k_i and a damping element b_i, the forces due to the joint flexibility are given by

$$\mathbf{F}_{flex}(\boldsymbol{\Theta})=\mathbf{K}(\boldsymbol{\theta}_{\mathbf{m}}-\mathbf{q}) \tag{34}$$

and

$$\mathbf{F}_{diss}(\boldsymbol{\Theta})=\mathbf{B}(\dot{\boldsymbol{\theta}}_{\mathbf{m}}-\dot{\mathbf{q}}) \tag{35}$$

On orbit, the potential energy due to the gravity is neglected. However, the potential energy due to joint flexibility is given by (5) and the dissipative loses caused by the damping elements at the joints are given by

$$T_{diss}(\mathbf{B},\dot{\boldsymbol{\theta}}_{\mathbf{m}},\dot{\mathbf{q}})=\int_{0}^{t}(\dot{\boldsymbol{\theta}}_{\mathbf{m}}-\dot{\mathbf{q}})^{\mathrm{T}}\mathbf{B}(\dot{\boldsymbol{\theta}}_{\mathbf{m}}-\dot{\mathbf{q}})dt \tag{36}$$

In the free-floating mode, only manipulator joints are activated. The energy provided by the joint actuators is

$$T_{m}=\int_{0}^{t}\boldsymbol{\tau}^{\mathrm{T}}\dot{\boldsymbol{\theta}}_{\mathbf{m}}dt \tag{37}$$

The energy generated by the actuators is balanced by the system kinetic and potential energy, and the dissipative loses due to damping. Therefore, the energy balance is written as

$$T_{m}=T+T_{flex}-T_{diss} \tag{38}$$

where the terms T_m, T, T_{flex} and T_{diss} are given by the Eqs. (37), (33), (5) and (36), respectively.

According to the above equations, the energy balance of a flexible-joint FFSMS is given by:

$$\begin{aligned}T_{m}=&\frac{1}{2}{}^{\mathbf{0}}\boldsymbol{\omega}_{\mathbf{0}}^{\mathrm{T}}\,{}^{\mathbf{0}}\mathbf{D}^{*}\,{}^{\mathbf{0}}\boldsymbol{\omega}_{\mathbf{0}}+{}^{\mathbf{0}}\boldsymbol{\omega}_{\mathbf{0}}^{\mathrm{T}}\,{}^{\mathbf{0}}\mathbf{D}_{\Theta}\dot{\boldsymbol{\Theta}}+\frac{1}{2}\dot{\boldsymbol{\Theta}}^{\mathrm{T}}\mathbf{D}_{\Theta\Theta}\dot{\boldsymbol{\Theta}}\\ &+\frac{1}{2}(\boldsymbol{\theta}_{\mathbf{m}}-\mathbf{q})^{\mathrm{T}}\mathbf{K}(\boldsymbol{\theta}_{\mathbf{m}}-\mathbf{q})-\int_{0}^{t}(\dot{\boldsymbol{\theta}}_{\mathbf{m}}-\dot{\mathbf{q}})^{\mathrm{T}}\mathbf{B}(\dot{\boldsymbol{\theta}}_{\mathbf{m}}-\dot{\mathbf{q}})dt\end{aligned} \tag{39}$$

It turns out that Eq. (39) can be written in a linear form with respect to the dynamic parameters

$$T_{m}=\mathbf{Y}_{\mathbf{EB}}(\dot{\mathbf{q}},\mathbf{q},\dot{\boldsymbol{\theta}}_{\mathbf{m}},\boldsymbol{\theta}_{\mathbf{m}},{}^{\mathbf{0}}\boldsymbol{\omega}_{\mathbf{0}})\boldsymbol{\pi}_{\mathbf{EB}} \tag{40}$$

where $\mathbf{Y}_{\mathbf{EB}}$ is the regressor matrix and the vector of the parameters to be estimated $\boldsymbol{\pi}_{\mathbf{EB}}$ contains all the necessary parameters required to define the full dynamics of a flexible-joint FFSMS.

It is important to note that the application of the estimation method based on the energy balance is tolerant to sensor noise since it requires only measurements of the spacecraft angular velocity ${}^{0}\boldsymbol{\omega}_{0}$, the manipulator link and motor angles $\mathbf{q}$ and $\boldsymbol{\theta}_{\mathbf{m}}$, and the corresponding velocities $\dot{\mathbf{q}}$ and $\dot{\boldsymbol{\theta}}_{\mathbf{m}}$ which do not contain significant noise.

If N measurements of these variables are obtained at given time instants $t_1, t_2, \ldots, t_N$ along an appropriate trajectory, the vector of the estimated parameters $\boldsymbol{\pi}_{\mathbf{EB}}$ can be computed by a least-squares technique

$$\boldsymbol{\pi}_{\mathbf{EB}} = (\hat{\mathbf{Y}}_{\mathbf{EB}}^{\mathrm{T}} \hat{\mathbf{Y}}_{\mathbf{EB}})^{-1} \hat{\mathbf{Y}}_{\mathbf{EB}}^{\mathrm{T}} \hat{T}_m \tag{41}$$

V. SIMULATION RESULTS

Example 1: The planar 7-DoF FFSMS system shown in Fig. 3 with parameters in Table I is employed to illustrate the proposed method. The 4 DoFs correspond to the two flexible joints and the other 3 DoFs describe the planar motion of the base of the FFSMS. The motor inertial properties as well as the properties of the flexible drive are presented in Table II. The angular momentum of the system is $h_{CM} = 1 Nms$.

For this planar space manipulator, the property of the linearity of the angular momentum conservation with respect to a vector of the estimated parameters, (19), yields:

$$h_{CM} = \mathbf{Y}_{\mathbf{h}}(\dot{\mathbf{q}}, \mathbf{q}, \dot{\boldsymbol{\theta}}_{\mathbf{m}}, \theta_0, \dot{\theta}_0)\boldsymbol{\pi}_{\mathbf{h}} \tag{42}$$

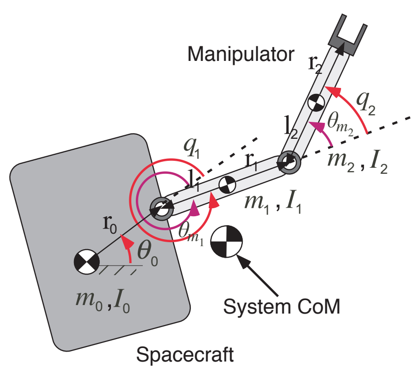

Fig. 3. A Planar 7-dof flexible-joint FFSMS and its main parameters.

Table I. Parameters of the 3 body planar system.

Body	m_i (Kg)	l_i (m)	r_i (m)	I_i (Kg m^2)
0	4000	-	5.0	666.7
1	200	5.0	5.0	33.3
2	1000	2.5	2.5	50.0

Table II. Parameters of the motors and the drive mechanisms.

Motor	n_i	k_i (Nm/rad)	b_i (Nms/rad)	m_{mi} (Kg)	I_{mi} (Kg m^2)
1	50	1000	75	1.0	1.0
2	50	1000	85	1.0	1.0

The vector of the estimated parameters $\boldsymbol{\pi}_{\mathbf{h}}$ is given by:

$$\boldsymbol{\pi}_{\mathbf{h}} = \begin{bmatrix} a_{00}^{*} & a_{01}^{*} & a_{02}^{*} & a_{11}^{*} & a_{21}^{*} & a_{22}^{*} & I_{m_1} & I_{m_2} \end{bmatrix}^{\mathrm{T}} \tag{43}$$

where I_{m_i} is the moment of inertia of the rotor i with respect to its axis, and $a_{ij}^{*}, (i,j = 0,1,2)$ are combinations of spacecraft, manipulator and motor parameters, and given in [12].

Note that the vector of the estimated parameters does not contain any of the parameters that describe the joint flexibility and thus, as mentioned before, this method cannot estimate the full dynamics of a flexible-joint FFSMS.

However, the properties of the linearity of equations of motion and the system energy balance equation with respect to a vector of estimated parameters yield, respectively

$$\mathbf{Q}^{*} = [\,\mathbf{0}^{\mathrm{T}}\ \mathbf{Q}^{\mathrm{T}}\,]^{\mathrm{T}} = \mathbf{Y}_{\boldsymbol{\tau}}(\ddot{\mathbf{q}}, \dot{\mathbf{q}}, \mathbf{q}, \ddot{\boldsymbol{\theta}}_{\mathbf{m}}, \dot{\boldsymbol{\theta}}_{\mathbf{m}}, \boldsymbol{\theta}_{\mathbf{m}}, \theta_0, \dot{\theta}_0, \ddot{\theta}_0)\boldsymbol{\pi}_{\boldsymbol{\tau}} \tag{44}$$

and

$$T_m = \mathbf{Y}_{\mathbf{EB}}(\dot{\mathbf{q}}, \mathbf{q}, \dot{\boldsymbol{\theta}}_{\mathbf{m}}, \boldsymbol{\theta}_{\mathbf{m}}, \dot{\theta}_0)\boldsymbol{\pi}_{\mathbf{EB}} \tag{45}$$

where the vectors of the estimated parameters $\boldsymbol{\pi}_{\boldsymbol{\tau}}, \boldsymbol{\pi}_{\mathbf{EB}}$ also contain the parameters characterizing the joint-flexibilities:

$$\boldsymbol{\pi}_{\boldsymbol{\tau}} = \boldsymbol{\pi}_{\mathbf{EB}} = \begin{bmatrix} \boldsymbol{\pi}_{\mathbf{h}}^{\mathrm{T}} & k_1 & k_2 & b_1 & b_2 \end{bmatrix}^{\mathrm{T}} \tag{46}$$

The vector $\boldsymbol{\pi}_{\mathbf{h}}$ is given by (43) and the parameters k_i and b_i describe the flexibility of joint i.

The N measurements required for the construction of the regressor matrices $\hat{\mathbf{Y}}_{\boldsymbol{\tau}}$ and $\hat{\mathbf{Y}}_{\mathbf{EB}}$ appear in (27) and (41), respectively, and are obtained employing exciting trajectories $q_i^d, i = 1,2$ given by:

$$q_i^d = A_i \sin(\omega_i t) \tag{47}$$

The paremeters were chosen as $A_1 = 20^0$, $\omega_1 = 0.25\text{rad/s}$ for the first and $A_2 = 40^0$, $\omega_2 = 0.5\text{rad/s}$ for the second joint.

The gyro measurements were simulated using (28) and (29) with standard deviations $\sigma_{\omega} = 3.1623 \cdot 10^{-4}\, \mu rad / s^{3/2}$ and $\sigma_{b\omega} = 0.31623\, \mu rad / s^{1/2}$ respectively, and with initial bias $b_{\omega,0} = 0.1\deg / hr$ [14]. The encoder noise, velocity and acceleration variances are given by (32), where the sample period is chosen as $\Delta T = 0.05\text{s}$. The precision q depends on the encoder counts; for a 500 counts encoder, it can be set equal to $q = 0.003\text{rad}$. Thus

$$\begin{aligned} \sigma_{pos}^2 &= 0.00025\text{rad} \\ \sigma_{vel}^2 &= 0.2\frac{\text{rad}}{\text{s}} \\ \sigma_{accel}^2 &= 128{,}000\frac{\text{rad}}{\text{s}^2} \end{aligned} \tag{48}$$

A PD controller is applied to the system with gains given by the following 2×2 matrices

$$\mathbf{K}_{\mathbf{P}} = \text{diag}(1000, 1000), \mathbf{K}_{\mathbf{D}} = \text{diag}(250, 250) \tag{49}$$

The estimated parameters obtained by the DE and EB methods are given by the solution of (27) and (41), respectively. The actual parameters and the results of the identification methods DE and EB, using measurements *with noise*, are displayed in Table III.

Table IV shows the corresponding relative errors, with respect to the actual parameters, of both methods using measurements with and without noise. As it can be shown in the second and third column of Table IV, in the case *without noise* in the measurements, both methods estimate the required parameters almost exactly. However, when noisy measurements are introduced, the DE method fails to identify the parameters, displaying errors between 21 and 144%, see fourth column of Table IV. In contrast to these results, the developed EB method, exhibits errors that are 3-207 times smaller than those obtained with the DE method (fifth column of Table IV), since the EB method does not require noisy acceleration measurements.

Table III. Actual and estimated parameters with the DE and EB methods.

π	Actual values $\times 10^4$	Estimated values (DE) $\times 10^4$	Estimated values (EB) $\times 10^4$
a_{00}	2.3774	4.7320	2.2731
a_{01}	4.2330	8.4258	4.0615
a_{02}	0.9612	1.9129	0.9168
a_{11}	8.1832	16.2882	7.8909
a_{21}	1.9709	3.9231	1.8933
a_{22}	0.5099	1.0150	0.4888
I_{m_1}	0.0001	0.00017	0.00010
I_{m_2}	0.0001	0.00012	0.00010
k_1	0.1000	0.1669	0.0919
k_2	0.1000	0.1553	0.0978
b_1	0.0085	0.0207	0.0077
b_2	0.0075	0.0120	0.0071

Table IV. Results from the DE & EB methods with & without noise.

π	Without noise		With noise	
	Relative Error (%) (DE) $\times 10^{-8}$	Relative Error (%) (EB) $\times 10^{-6}$	Relative Error (%) (DE)	Relative Error (%) (EB)
a_{00}	0.1645	-0.1720	-99.0396	-4.3859
a_{01}	0.1646	-0.0901	-99.0497	-4.0512
a_{02}	0.1646	-0.1169	-99.0108	-4.6137
a_{11}	0.1646	-0.0166	-99.0439	-3.5711
a_{21}	0.1645	-0.0403	-99.0507	-3.9361
a_{22}	0.1644	-0.0652	-99.0478	-4.1264
I_{m_1}	0.0434	0.1119	-72.3263	-0.3497
I_{m_2}	0.0344	-0.1614	-20.8492	-6.4170
k_1	0.0871	-0.1358	-66.8517	-8.0512
k_2	0.0928	-0.1024	-55.3035	-2.1779
b_1	0.1594	-0.2205	-143.7792	-9.1603
b_2	0.0843	0.3829	-60.4581	-5.4391

Next, we investigate if the above estimated parameters obtained by the EB method can describe the full dynamics of the flexible-joint FFSMS sufficiently.

Considering the system dynamics, given by (14), one can study the response of the system by applying a desired torque on the joint motors. The applied torque input is given by,

$$\boldsymbol{\tau} = \begin{bmatrix} 0.5\cos(t) \\ 0.1\cos(0.1t) \end{bmatrix} Nm \tag{50}$$

Two cases are considered. First, the system dynamics is described by the estimated values obtained by the EB method in Example 1 and shown in the fourth column of Table III. In the second case, the parameter values are set with errors $\pm 10\%$ of their nominal values. The response for each case is compared with the actual system response (i.e. the response using the actual system parameters, as given in the second column of Table III).

Fig. 4a shows the response of the link angles of the system shown in Fig. 3, considering (i) the actual system parameters, (ii) the estimated parameters by the proposed EB method and (iii) the parameters with error $\pm 10\%$. The corresponding relative errors in the responses are presented in Fig. 4b. As can be observed, the resulting response obtained by using the parameters estimated by the EB method is very satisfactory compared with the response obtained by parameters with $\pm 10\%$ error, since the former follows the system actual response while the latter exhibits a continuously diverging error. Therefore, one can conclude that the estimated parameters obtained by the EB method can describe the full dynamics of the flexible-joint FFSMS sufficiently.

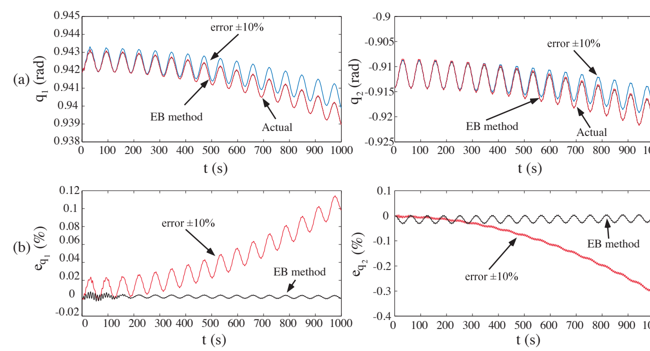

Fig. 4. (a) The response of the link angles considering (i) the actual system parameters, (ii) the estimated by EB method and (iii) parameters with error $\pm 10\%$, (b) the corresponding % relative errors.

VI. Conclusions

In this paper, the estimation of full dynamics of a space manipulator system with joint flexibilities in the free-floating mode was studied. It was shown that the methods based on the angular momentum conservation, although they are insensitive to sensor noise, they cannot estimate the joint flexibility parameters. Here, a parameter estimation method, which is based on the energy balance during the motion of a flexible-joint FFSMS was developed. The method estimates all system parameters including those that describe the joint flexibilities, and requires only measurements of joint angles and rates, spacecraft attitude and angular velocity, and joint torques. In contrast to the methods based on the equations of motion, the developed method is insensitive to sensor noise, since no information about spacecraft and joint accelerations, is required. The application of the proposed method is valid for spatial systems. It was shown that the parameters estimated by the proposed method describe the system full dynamics sufficiently**.** The method was illustrated by a planar 7 degrees of freedom (DoF) flexible-joint FFSMS.

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